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Schmidt, Björn; King, John; Larsen, Gunner Chr.; Larsen, Torben J.

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Load validation and comparison versus certification approaches of the Risø Dynamic Wake Meandering model implementation in GH Bladed

Björn Schmidt
Germanischer Lloyd
Renewables Certification
bjoern.schmidt@gl-group.com

John King
GL Garrad Hassan
John.King@gl-garradhassan.com

Gunner C. Larsen
Risø DTU
National Laboratory for
Sustainable Energy
gula@risoe.dtu.dk

Torben J. Larsen
Risø DTU
National Laboratory for
Sustainable Energy
tjul@risoe.dtu.dk

Abstract

The present paper outlines the Risø Dynamic Wake Meandering model (DWM) [1], that has been improved within the EU research project TOPFARM, its implementation into the wind turbine load calculation software GH Bladed and the subsequent load validation.

The new Bladed DWM module is compared against two measurement campaigns. The first validation, against data from the EU project Dynamic Loads in Wind Farms [12], indicated quantitatively good agreements for blade root flapwise bending moment and yaw torsion.

The second campaign referred to measurements from the Horns Rev offshore wind farm. The related validation indicated quantitatively good agreement for the blade root flapwise bending moment and the tower base overturning moment in the operational region below and above rated power. Discrepancies between measurement and simulation in the wake affected tower base overturning moment around rated power are deemed to be caused by free flow load differences, not by the wake model.

A fatigue load comparison of the Bladed DWM model with the commonly used effective turbulence intensity approach from the IEC 61400-1 Standard was performed. The result suggested that the IEC approach is conservative at low turbine spacings but may under predict wake loads for spacings larger than 5 rotor diameters (D).

Keywords: Wake, wind farm, load, measurement, offshore, validation.

1 Introduction

Wind turbine wakes effect the downstream wind field and increase dynamic loads for downstream turbines. The growing scale of wind farms, particularly in combination with low ambient turbulence intensity offshore, significantly increases the wake affected turbine loading. Consequently, the need arose to improve wake induced wind field modelling. One main question governing the analysis of offshore wind farms is whether the existing methods are conservative and how much room for optimization exists.

Within the TOPFARM research project (EU project reference No.: 38641) a wake model, developed by Risø DTU, has been improved. This Dynamic Wake Meandering (DWM) model has been implemented in the wind turbine load simulation software GH Bladed. Load validation of the Bladed DWM model against two load measurement campaigns has been performed.

Additionally, a fatigue load study was performed to compare load results from the Bladed DWM model with results from the approach recommended in the IEC 61400-1 Standard. This approach, widely known as the Frandsen effective turbulence model [3], is commonly used for design and certification purposes by the industry to predict wake affected wind turbine loading.

2 The DWM model

The basic philosophy of the DWM model is a split of scales in the wake flow field, based on the conjecture that large turbulent eddies are responsible for stochastic wake meandering only, whereas small turbulent eddies are responsible for wake attenuation and expansion in the meandering frame of reference as caused by turbulent mixing. It is consequently assumed that the transport of wakes in the atmospheric boundary layer (ABL) can be modelled by considering the wakes to act as passive tracers driven by a combination of large-scale turbulence structures and a mean advection velocity, adopting the Taylor hypotheses.

The DWM model is essentially composed of three corner stones:

1. A model of the wake deficit as formulated in the meandering frame of reference
2. A stochastic model of the down-stream wake meandering process
3. A model of the self induced wake turbulence, described in the meandering frame of reference.

Detailed descriptions of the various sub-models and their implementation in the framework of the aeroelastic code HAWC2 can be found in [1], [8], [9] and [10]. A brief introduction is given in the following.

The modelling of the wake deficit is based on the thin shear layer approximation of the Navier-Stokes equations in their rotational symmetric form, and includes wake expansion and attenuation as function of downstream transportation time, caused partly by turbulent mixing and partly by rotor pressure field recovery [9].

The turbulent mixing is modelled by expressing the relevant Reynolds stresses in terms of mean flow variables using an eddy viscosity approach. Both the high frequency part of the ABL turbulence and the self induced wake turbulence are accounted for in the formulation of the turbulent eddy viscosity.

As for the stochastic modelling of wake meandering, the wake is assumed to be constituted by a cascade of wake deficits [8],

each “emitted” at consecutive time instants in agreement with the passive tracer analogy. We then describe the propagation of each “emitted” wake deficit, the collective description of which constitutes the wake meandering model.

The self induced turbulence concerns small-scale turbulence with characteristic eddy sizes up to approximately one rotor diameter. These include contributions from conventional mechanically generated turbulence caused by the wake shear, as well as from the blade bound vorticity consisting mainly of tip and root vortices. These vortices will initially take the form of organized coherent flow structures, but later gradually break down due to instability phenomena, and approach the characteristics of conventional isotropic inhomogeneous turbulence with a length scale shorter than that of atmospheric turbulence [1], [11]. In the present version of the DWM approach, the self induced turbulence is obtained from a simple scaling of a conventional homogeneous turbulence field, using empirically determined scaling factors depending on the radial rotor coordinate and related to the magnitude of the wake deficit as well as to the wake shear at the particular downstream distance [9].

3 Bladed DWM software

The wind turbine simulation software used for the Alsvik load measurement comparison is GH Bladed with the DWM wake simulation module. For the Horns Rev comparison the GH Bladed version 4.0, which includes a multi-body formulation of the structural dynamics, and the DWM wake module were used.

The DWM module allows a dynamic wake deficit to be superimposed on top of ambient turbulence. The sections below describe the components of the dynamic wake meandering model.

3.1 Meandering time history generation

Within Bladed, the wind file governing the meandering motion is generated from a low pass filtered turbulence spectrum. The wind

file velocities resulting from the reverse Fourier transform of this turbulence spectrum are therefore those associated with the low frequency components of the turbulence. The low pass frequency f_c suggested by Risø [8] for ambient turbulence-wake interaction is defined as:

$$f_c = \frac{U}{2D} \quad (1)$$

U = mean wind speed

D = Rotor diameter of affecting turbine

The low frequency components of the turbulence govern the lateral and vertical transportation of the wake deficit downstream. Since the wind file has been generated to only include the velocities that interact with the wake, no further filtering or processing of the velocities is required.

The meandering displacement time history is based on the 'cascade of deficits' model reported by Risø [8]. This assumes a deficit is released at each time step within a frozen turbulent wind field. The transportation of each deficit is governed solely by the velocity that it encounters as it is released into the frozen turbulent wind field.

Therefore the lateral $y(t)$ and vertical $v(t)$ displacement at downwind position L_d is equal to:

$$y(t) = v(t) \cdot \left(\frac{L_d}{U} \right) \quad (2)$$

$$z(t) = w(t) \cdot \left(\frac{L_d}{U} \right) \quad (3)$$

$v(t)$ = lateral velocity

$w(t)$ = vertical velocity

3.2 Wake deficit velocity profile and propagation

The existing Eddy Viscosity Model proposed by Ainslie [13] initialises with an induced pressure-expanded velocity deficit. The Ainslie model is based on the thin shear layer approximation of the Navier-Stokes equation. The Reynolds stress terms governing the transfer of momentum from

the ambient turbulence to the wake at each downwind position are approximated with an eddy viscosity proportional to the width of the deficit shear layer and the shear velocity gradient.

4 Validation versus Alsvik load measurements

Dynamic Loads in Wind Farms [12] was a European Community Joule Project published in 1996 which aimed to achieve a greater understanding of the behaviour and loading of wind turbines operating within wind farms. The report aimed to provide wind turbine measurement data against which a range of turbine fatigue load predictive tools could be validated.

The GH Bladed DWM model was compared against loading data from the Alsvik wind farm located on the west coast of Gotland. Alsvik consists of four Danwin 180kW, fixed speed, stall regulated wind turbines.

The Alsvik loading data was selected for comparison as there were several measurement campaigns with wake affected operation at constant turbine spacing, including a wide variety of wake offsets. The measurements taken from the Danwin turbine consist of 10-minute mean standard deviations of tower top torsion moment and blade root flapwise bending moment. The Alsvik data was presented for wind speed bins 7-9m/s, 9-11m/s and 11-13m/s. The ambient turbulence intensity was approximated at between 5 and 6%.

Using data obtained from Adams [12], a Bladed model of the Danwin 180kW turbine was constructed. Three meandering seeds per wind speed were generated from the low pass filtered von Karman turbulence spectrum for each mean wind speed.

The mean of the meandering seeds was plotted alongside the measured data for two wind speed bins. Figure 1 displays the predicted and measured standard deviation of yaw torsion for wind speed bin 7-9m/s. The Bladed DWM model shows good agreement with the measured data. The shape of the loading has been captured

well. The Bladed DWM model predicts the boundaries of the central peaks, the steep slopes either side, and the ambient loading at the extremes of the graphs with a good degree of accuracy.

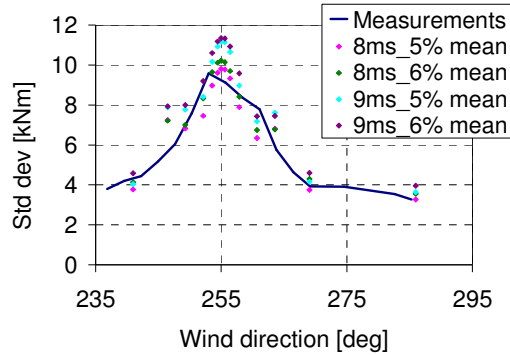


Figure 1: Yaw torsion standard deviation [Wind bin 7-9m/s]

Figure 2 displays the predicted and measured standard deviation of blade root flapwise bending moment for wind speed bin 7-9m/s. The Bladed DWM model shows good agreement with the measured data. The shape of the loading has been captured well. The model predicts the central dip, the peaks around 250 and 260 degrees, and the ambient loading at the extremes of the graphs with a good degree of accuracy.

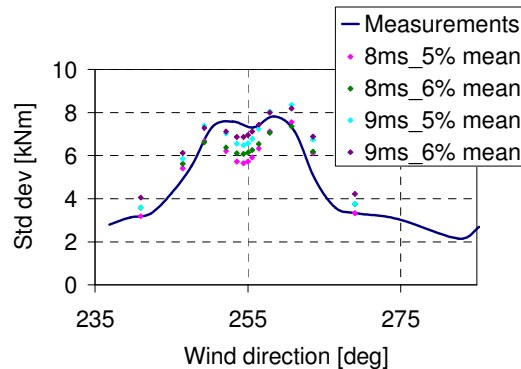


Figure 2: Blade root flapwise standard deviation [Wind bin 7-9m/s]

5 Validation versus Horns Rev measurements

Horns Rev, the first “big” offshore wind farm, was installed in 2002 about 15km off the westernmost point of Denmark, Blåvands

Huk. The wind farm consists of 80 Vestas V80 turbines on monopile support structures, of which turbine No. 14 was equipped with measurement gear. The turbines have a rotor diameter of 80m and a hub height of 70m with reference to Mean Sea Level (MSL). The location of turbine No. 14 is in the second column and the fourth row, with prevailing winds from the West. Consequently, wake situations caused by a single turbine wake are expected at three different spacings: 7D, 9.4D and 10.4D, see Figure 3.

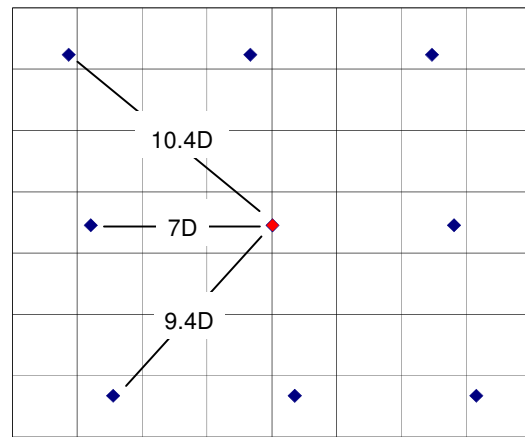


Figure 3: Detail of Horns Rev wind farm, showing the neighbouring direct wake affecting turbines for wind turbine No. 14 (red).

Turbine No. 14 was instrumented for load measurements at the blade root, the drive train, main frame and several tower stations including the tower base at 13m above MSL. Due to broken sensors or irreversible miscalibrations, only the blade flapwise moment and the tower base bending moment sensors were usable for the wake load studies reported herein [14, 15]. The 20Hz sampled load measurement data covers the periods of 2006 and 2007 [14].

A V80 turbine mathematical model, originating from the planning phase of the Horns Rev wind farm, was updated according to the structural data of turbine No. 14 [15]. The updates included the location specific water depth of 10m MSL and a tuning of the foundation stiffness according to the measured first natural bending frequencies of the turbine with support structure.

5.1 Uncertainties

Measurement equipment maintenance

The load measurement equipment was not maintained regularly, so it is expected to contain errors due to shifting calibration factors with time that may significantly affect the load measurement results of the present validation [15].

Turbulence

No met mast free flow wind speed and direction signals exist for the time period of load measurements used (2006-2007). Thus, the ambient hub height turbulence intensity employed for the simulation was derived as the annual mean from a time period prior to the measurement campaign. This data originated from met mast M2 that is located west of the wind farm in the free inflow sector. As met mast M2 measurements had only been available for 15m and 45m LAT [18], the turbulence values were extrapolated to the hub height of 70m above MSL under the assumption of a height independent standard deviation of the mean wind speed, in accordance to the IEC Standard [3]. The resulting ambient turbulence intensity at hub height is illustrated in the Figure 4 and compares well to recent studies (2010) from Hansen and Barthelmie [16].

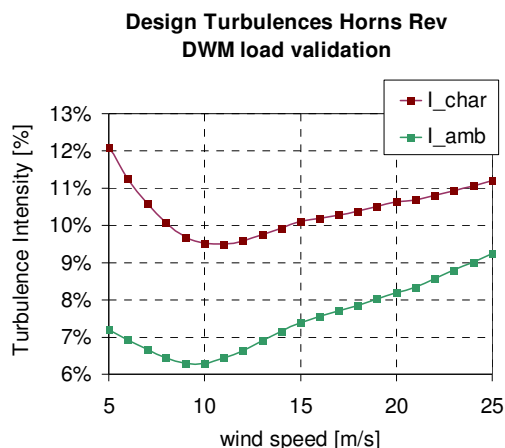


Figure 4: Comparison of the ambient and the characteristic (90% quantile) turbulence intensities for the offshore wind farm Horns Rev.

The simulations took into consideration the Horns Rev Vestas V80 specific mean yaw misalignment of $\pm 6^\circ$. The turbulence model used was the improved von Karman (ESDU)

model that is considered appropriate for offshore conditions.

Wind speed reference

The wind direction uncertainty is estimated to $\pm 2^\circ$ [18]. More uncertainty occurred when correlating the mast wind speed with the load measurements. Due to the fact that no time corresponding free flow wind speed was available, the statistics of turbine No. 14's SCADA system were used. The drop in 10-minute mean wind speed directly behind the rotor, from where the anemometer delivers the SCADA system input, is quite hard to estimate, as several effects, e.g. wake effects and pressure gradients around the nacelle, may play an important, but unknown role. Comparison of the SCADA data with data from met mast M6, located 2km east (downstream of the prevailing wind direction) of the Horns Rev wind farm, indicated comparable mean wind speeds between M6 and the SCADA system with differences below 2%. Previous studies by Jensen [17] comparing met mast M6 with the free inflow met mast M2 indicated that the mean wind speed difference between M2 and M6 is below 10%. The impact of using the SCADA mean wind speed and other uncertainties were addressed by normalizing the wake affected loads by the free inflow loads.

Finally, additional uncertainty originated from a lack of synchronization between the load sensor time series and the SCADA data. This ranged from between 1 to 5 minutes [14].

Turbine control system

During analysis of the turbine's operational control algorithm, it was recognized that the control algorithm used for modelling was simplified compared to the real one. The real Horns Rev Vestas V80 controller uses an optimum minimum pitch angle that varies as a function of wind speed. This pitch schedule information was not available for implementation in the controller used within Bladed. The omission may have led to load deviations in turbulent flow cases between measurement and simulation in the region below and around rated power.

Another important consideration is the deviation between measured and simulated power output in the part-load region (under free flow conditions). The part-load

simulations were approximately 10% higher than the measurements. This may be an effect of the wind speed measurement error, the controller settings or the aerodynamics assumptions.

To address the uncertainties described, the free inflow loads had been examined and the wake loads were, if possible, subsequently normalized by the free inflow loads.

5.2 Results

Blade flapwise bending moment

For free inflow conditions the resulting damage equivalent load (DEL) of the blade root flapwise bending moment, with an equivalent frequency of 1Hz is shown in Figure 5 for an SN curve exponent of $m=12$.

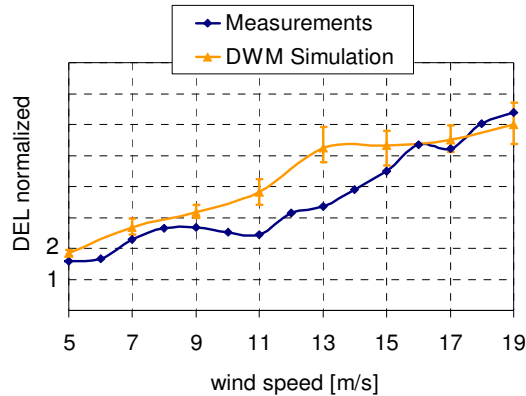


Figure 5: Free inflow blade root flapwise bending moment 1Hz DEL ($m=12$).

The free flow blade flapwise moments between the Bladed DWM simulations and the measurements compare quite well, apart from the region around rated wind speed. From the measurements, rated wind speed was found to be about 12m/s. Discrepancies in the control system implementation may cause this difference.

Of importance is the fact that the DWM simulation yields conservative results.

The following graphs (Figures 6-8) show the wake-affected blade root flapwise bending moment DEL ($m=12$, 1Hz) for the different spacings 7D, 9.4D and 10.4D from the DWM Bladed simulation, the simulation with Bladed for the IEC ed.3 approach (see Section 6) and from load measurements. All

results are normalized with respect to (wrt) the free inflow loading, apart from the first graph for 7D, see Figure 6, upper graph. This graph shows non-freeflow normalized loads, as the free flow load normalization yielded results that appeared implausible, see Figure 6, lower graph. The discrepancy for 7D may be caused by a shift in the measurements. Compared to 9.4D and 10.4D, fewer measurements were available for 7D, thus, outliers from shifted measurements may have had a significant impact on the blade loads measured for 7D.

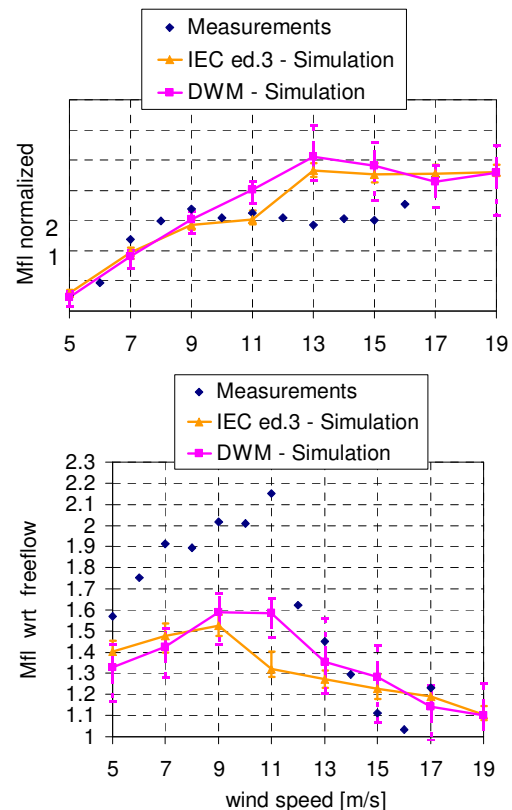


Figure 6: 7D spacing, blade root flapwise bending moment DEL ($m=12$) normalized with load factor (upper) normalized to free flow loading (lower).

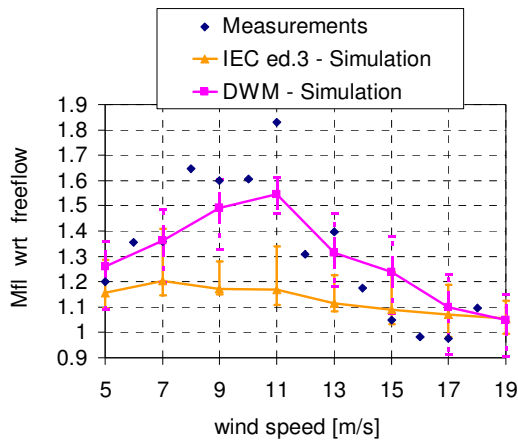


Figure 7: **9.4D** spacing, free flow normalized blade root flapwise bending moment DEL ($m=12$)

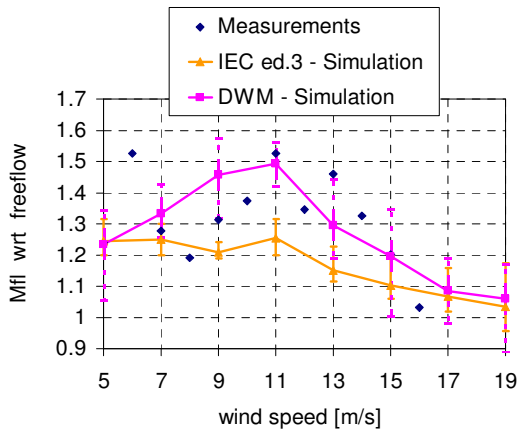


Figure 8: **10.4D** spacing, free flow normalized blade root flapwise bending moment DEL ($m=12$)

Conclusion for flapwise bending moment validation

The results support the findings of a previous study (see Chapter 6) by indicating that the IEC 61400-1 ed.3 approach may underestimate the blade root flapwise bending DEL for spacings larger than 7D. This is of significant importance, as the IEC ed.3 approach provides the most conservative design turbulence, and therefore loads, compared to the IEC ed.2 and the Amendment A to IEC ed.3 approaches. Furthermore, the findings indicate that the (normalized) DWM loads capture the (normalized) measured flapwise bending moments well. The deviations in the non-normalized part-load region for 7D are presumably related to differences in the control algorithms and/or impact from

shifting load measurements. Also of interest is the huge spreading of the DWM loads due to part-wake effects (yaw misalignment of ± 6 deg causes part wake cases). This emphasizes the importance of considering spacing dependent values for the yaw misalignment. It is recommended to further study this dependency which could include significance for the yaw torsional loading.

For illustration of the spacing influence, Figures 9-12 picture the analogue results of the $m=12$ blade flap moment DEL for wind speeds of 5, 9, 11 and 15 m/s. It becomes obvious that the free flow load normalization is inappropriate for 7D and that a deviance exists for 11 m/s, close to rated wind speed. Nevertheless, the DWM model generally shows the greatest agreement to the measurements and is more conservative than the IEC ed.3 approach.

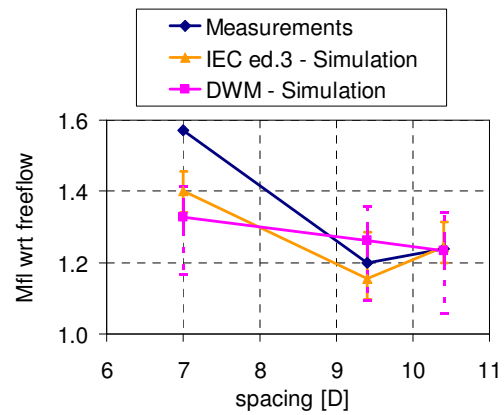


Figure 9: $v = 5$ m/s, $I_{amb} = 7\%$
free flow normalized blade root flapwise bending moment DEL ($m=12$).

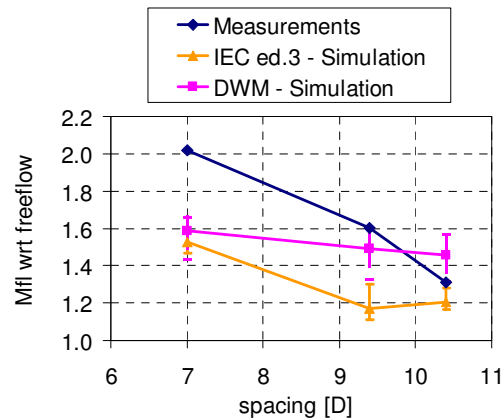


Figure 10: $v = 9$ m/s, $I_{amb} = 6\%$
free flow normalized blade root flapwise bending moment DEL ($m=12$).

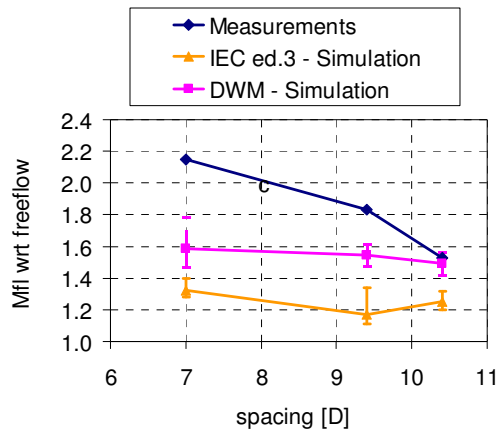


Figure 11: $v = 11 \text{ m/s}$, $I_{\text{amb}} = 6.5\%$
free flow normalized blade root flapwise bending moment DEL ($m=12$).

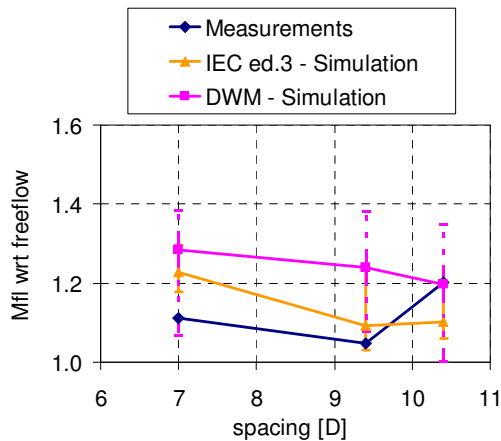


Figure 12: $v = 15 \text{ m/s}$, $I_{\text{amb}} = 7.5\%$
free flow normalized blade root flapwise bending moment DEL ($m=12$).

Tower bottom bending moments

The tower bottom ($h=13\text{m}$ LAT) loads were impossible to normalize to free flow loads. This was because no measured free flow loads existed for the wake inflow directions and because normalizing with free inflow from 294° led to wrong results (e.g. wake case bending moments at $9.4D$ - with wind from 221° - normalized with free flow bending moments at wind from 294°).

For free inflow conditions the resulting 1Hz damage equivalent load (DEL) of the tower bottom ($h=13\text{m}$ LAT) bending moments are shown in Figure 13-14¹ for an SN curve exponent of $m=4$.

Again, the free flow loads compare quite well with the exception of the region around rated wind speed, most notably for the bending moment which sees the greater share of the fore-aft movement (Figure 13). Checks performed for several optimum pitch angle settings were able to rule out this as a possible source of error. Other differences in the control algorithms are most likely the reason for the deviation around rated wind speed.

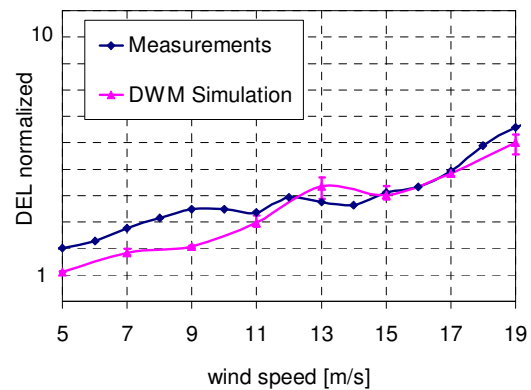


Figure 13: **Free flow, wind 294°** ,
NS -50° sensor,
tower bottom bending moment DEL ($m=4$).

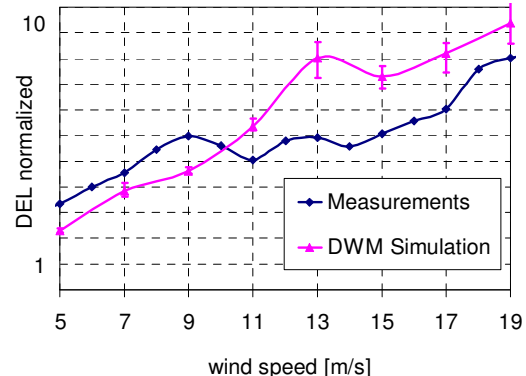
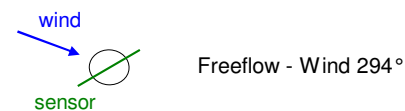


Figure 14: **Free flow, wind 294°** ,
NS+40° sensor,
tower bottom bending moment DEL ($m=4$, 1Hz).

¹ In the graphs, the drawing (left upper corner in each Figure) indicates the bending direction and the axis of the sensor, e.g. NS -50° in Figure 13 means the sensor was positioned 50° clockwise with respect to the North-South axis. If regarding the wind direction, fore-aft and side-side moments can be concluded.

The following graphs (Figures 15-16 for 9.4 and 10.4D spacing) show the wake-affected DELs ($m=4$, 1Hz) for those sensors which measured a bending moment close to the fore-aft direction.

For wind from 270°, corresponding to 7D spacing, both sensors measure a part of the fore-aft movement. Only the NS -50° bending moment sensor which measures a slightly larger fore-aft portion is shown in Figure 17.

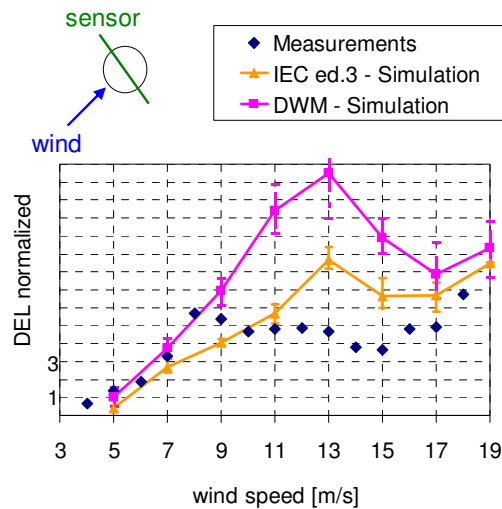


Figure 15: **9.4D, wind 221°**,
NS +40° sensor,
tower bottom bending moment DEL ($m=4$).

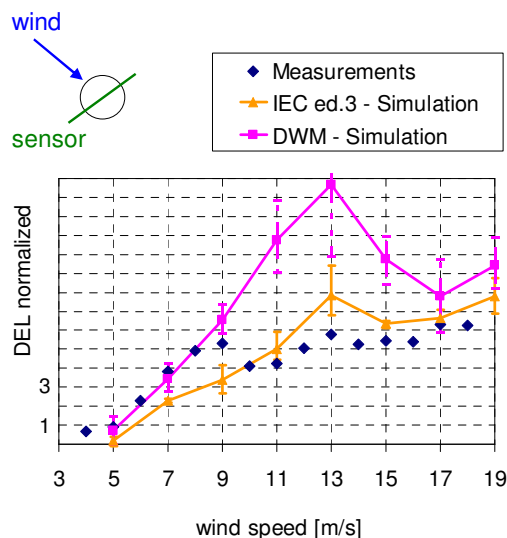


Figure 16: **10.4D, wind 313°**,
NS -50° sensor,
tower bottom bending moment DEL ($m=4$).

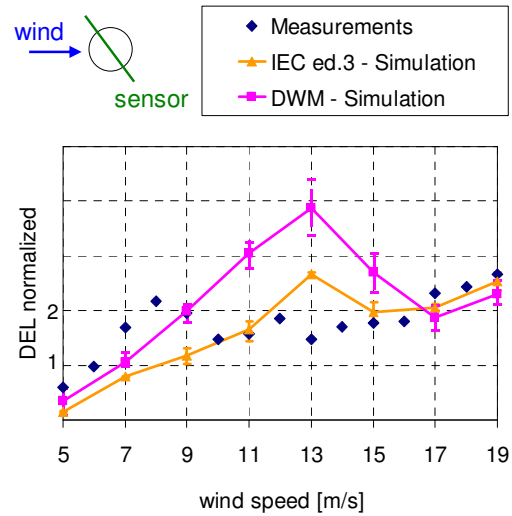


Figure 17: **7D, wind 270°**,
NS+40° sensor,
tower bottom bending moment DEL ($m=4$).

The measured loads compare to the DWM simulations in the below and above rated region only. The IEC ed.3 simulations seem to under estimate the overturning moment in that region but compare well around the rated region.

6 Load Comparison of DWM model to IEC Standard approaches

The IEC 61400-1 Standard (IEC Standard) recommends an approach that is widely known by the Frandsen studies to represent wake effects on wind turbine loading by an effective turbulence intensity [3]. This approach is commonly used for design and certification purposes by the industry, consultancies and certification bodies. In this study, differences among effective turbulence approaches as given in the IEC 61400-1 Standard in edition 2 [2], edition 3 [5] and the Amendment A to edition 3 [6] were analyzed for the NREL 5MW turbine [7]. The impact on the fatigue design turbulence I_{design} was studied for a direct full wake situation of two turbines and for several wind farm situations.

Furthermore, a two turbine fatigue load study was performed with the NREL 5MW

turbine [7] to compare the Bladed DWM simulation load outcome versus load results derived with the approach from the IEC Standard in edition 2 [2] and the method of Frandsen and Thøgersen [4].

The study considered a 10-min mean wind speed of 10 m/s, equally distributed wind in 2° steps from wind directions -30° to +30°, a characteristic ambient turbulence intensity (used for the ambient case simulation) of 10% and spacings of 3, 4, 6, 8 and 10D.

The DEL was derived via a rainflow cycle counting with 1E7 cycles in 1 year. The DWM postprocessing gave an equal weight (1/31) to each wind direction. The IEC ed.2 postprocessing weighted the simulations according to the Frandsen view angle [3] as wake affected (simulations with effective turbulence intensity) or non-wake affected (simulations with the characteristic ambient turbulence).

Conclusions of the two turbine study

The results of the two turbine comparison (damage equivalent load for SN curve exponents of $m=4$ and $m=10$) suggested that the effective turbulence approach is conservative at low turbine spacings over the full range of load components considered (blade root flapwise bending moment, hub thrust force, yaw torsion, tower top and tower base overturning moments), see Figures 18-19.

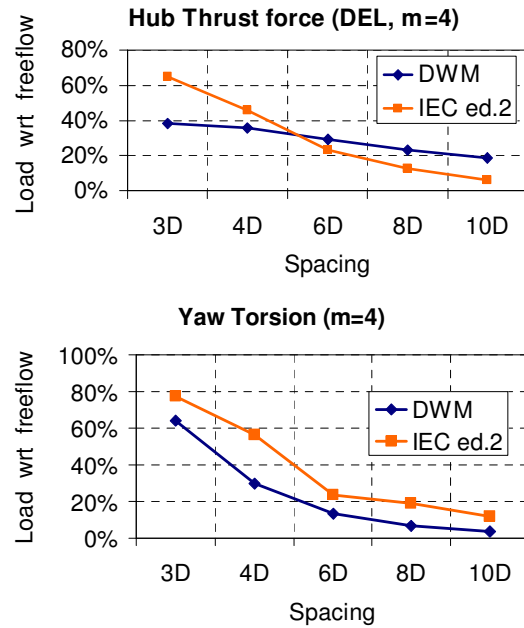
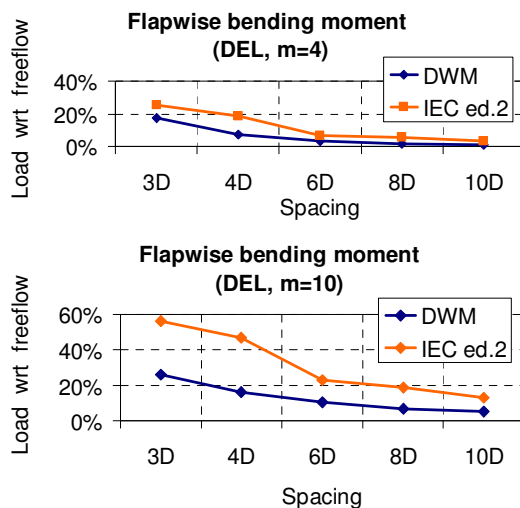
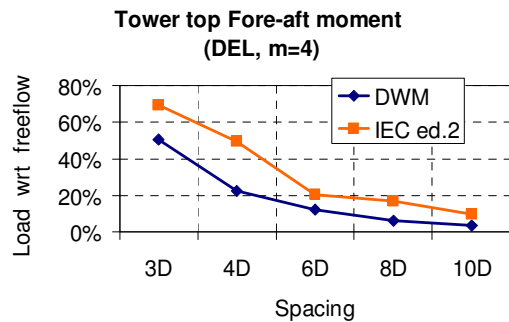


Figure 18: DEL for blade root, hub and yaw load components for the two turbine comparison of the DWM versus the IEC ed.2 approach.

Interestingly, the comparison also indicated that the Frandsen approach in the IEC ed.2 Standard may under predict wake effected fatigue loading at spacings larger than 5D for hub thrust force and tower base overturning moment. The load under prediction is emphasized for the IEC ed.3 for blade flapwise and tower base overturning moment at spacings of 9.4D and 10.4D by the results of the Horns Rev DWM validation.



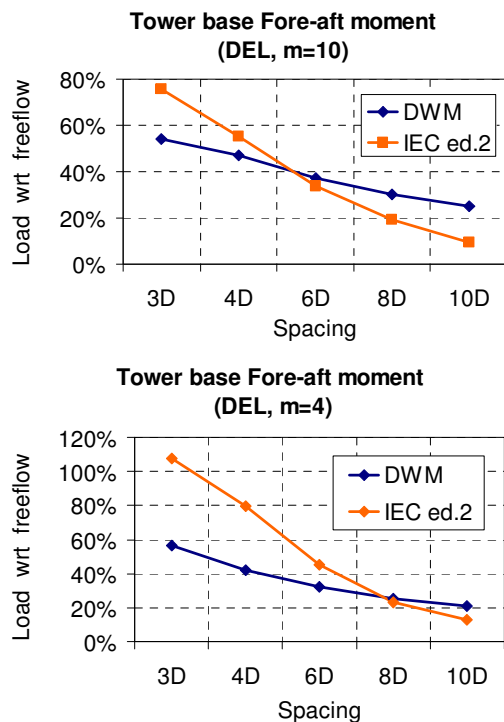


Figure 19: DEL for tower top and tower base load components for the two turbine comparison of the DWM versus the IEC ed.2 approach.

Recommendation for further research

The aspect of load under prediction for spacings larger than 5D may be influenced by the ambient turbulence level, the wind speed deficit and the wind direction distribution. This should be further investigated for turbine No.14 at the Horns Rev wind farm in the situation given by wakes from nine neighbouring turbines (Figure 3). For the IEC approaches wind farm wake effect should be considered as described in the different versions of the standard [2, 5, 6]. The load analysis will be conducted for the Bladed DWM model and all three existing IEC approaches, namely:

- IEC 61400-1, edition 2 [2] and the method of Frandsen [4]
- IEC 61400-1, edition 3 [5]
- IEC 61400-1, edition 3, Amendment A [6].

7 Conclusion

The Bladed DWM model improves the account for load impact from wind turbine wake influences.

The first validation, against data from the EU project Dynamic Loads in Wind Farms [12], indicated quantitatively good agreement for blade root flapwise bending moment and yaw torsional load components.

The second validation versus load measurements at the Horns Rev offshore wind farm indicated quantitatively good agreements for the blade root flapwise bending moment and for the tower base overturning moment in the below rated region. Discrepancies for the tower base over-turning moment around rated wind speed are deemed to be caused by free flow load differences (measurement to simulation), since free flow load and wake case load deviations were of comparable shape and order of magnitude.

Load comparison between the Bladed DWM model and the effective turbulence intensity approach of IEC ed.2 suggested that the approach is conservative at low turbine spacings. The approach may under predict wake effected fatigue loading at spacings larger than 5D for hub thrust force and tower base overturning moment.

The load validation for Horns Rev turbine No. 14 suggested that the IEC ed.3 approach may under predict wake effected fatigue loading for blade root flapwise bending moment and tower base overturning moment compared to the Horns Rev load measurements and Bladed DWM results for turbine spacings 7D, 9.4D and 10.4D.

The aspect of load under prediction for spacings larger than 5D will be further investigated by a 20-year fatigue analysis for turbine No.14 at the Horns Rev wind farm.

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